Dielectric Properties and Thermal Conductivity of Marinated Shrimp and Channel Catfish

M. ZHENG, Y.W. HUANG, S.O. NELSON, P.G. BARTLEY, and K.W. GATES

ABSTRACT

Peeled shrimp (*Peneaus* spp.) and channel catfish (*Ictalutus punctatus*) fillets were either mixed with commercial lemon pepper marinade and vacuum tumbled at 4°C for 30 min or soaked in 2% tripolyphosphate solution overnight. Dielectric constant and loss factor of marinated seafood and the penetration depth of microwaves were functions of temperature. When cooking temperature increased, the dielectric constant increased, while the loss factor and depth of penetration decreased. Because of the large variation in thermal conductivity measured for individual shrimp, no correlation between thermal conductivity and temperature was found. At constant temperature, thermal conductivity of 2% sodium tripolyphosphate-treated shrimp was higher than that of both marinated and nonmarinated shrimp as a result of higher moisture content. However, no difference in thermal conductivity was found between marinated and nonmarinated shrimp or catfish.

Key Words: shrimp, channel catfish, marination, dielectric properties, thermal conductivity

INTRODUCTION

SEVERAL FACTORS CAN AFFECT THE nonuniform heating characteristics of microwave processed foods. These generally include product geometry, thermal, physical and dielectric properties, and processing parameters such as microwave frequency, temperature, power applied and exposure time (Schiffmann, 1986). Thermal and dielectric properties of foods greatly affect the behavior of food during microwave cooking. In foods, thermal conductivity depends mostly on the amount and structuring of different components — especially water (Sweat, 1986). The dielectric constant determines the amount of energy reflected from the product and transmitted into the product. Loss factor describes how well a material absorbs energy from electric fields passing through it and converts that energy to heat. Both are affected by microwave frequency, cooking temperature, material density, water content, salt content and the state of foods, such as frozen or fresh (Ohlsson et al., 1974; To et al., 1974; Tong and Lentz, 1993).

Thermal and dielectric properties of raw agricultural materials have been compiled in many references (Choi and Okos, 1983; ASHRAE, 1985). Dielectric properties of some food products have been reported (Tinga and Nelson, 1973; Kent, 1987). However, little information on processed products has been published. The thermal and dielectric properties of value-added fresh foods and prepared chilled foods are changed with the addition of cooking condiments during manufacture. Therefore, the behavior of such foods in microwave cooking may be changed. It is necessary to measure the thermal and dielectric properties of those types of chilled foods in order to develop safe microwave cooking procedures.

Marination has gained popularity in the meat industry. The processing involves incorporation of spices, salts, sugars, and acidic solutions into products. It improves the cooking yield, juiciness and tenderness of products as water holding capacity is increased (He, 1996). Marinated seafood has become a popular microwaveable product as it is convenient to cook and comes in a variety of flavors. However, no information regarding the thermal and dielectric properties of marinated seafood is available. Our objectives were to determine the changes in thermal and dielectric properties of shrimp and catfish as affected by cooking temperature and marination.

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MATERIALS & METHODS

Samples

Shrimp (*Peneaus* spp.) were caught off the coast of Brunswick, GA. and frozen into 2.27 kg blocks at −20°C after heads were removed. The shrimp size was 66–77 count/kg. Live channel catfish (*Ictalutus punctatus*) were purchased from the Dekalb Farmers Market, Atlanta, GA. After being cleaned and filleted, catfish were covered with ice and transported to Athens, GA. Both shrimp and catfish were stored at −20°C until processed.

Marination

Peeled shrimp and catfish fillets were mixed with commercial lemon pepper marinade (Formula 159-J., A.C. Legg. Packing Company, Inc., Birmingham, AL) and vacuum-tumbled (22 psi) in an Inject Star Systems (Globus Laboratories Inc., South Hackensack, NJ) at 4°C for 30 min. The formula for marination product was 11.35kg shrimp or catfish fillet, 0.79 kg water, and 0.23 kg marinade. The marinade formula consisted of salt, dextrose, sodium phosphates (20.69%), black pepper spice extractives and lemon oil. Marinated samples were stored at 4°C for 10 h before determination of dielectric properties and thermal conductivities.

To get a high weight gain, peeled shrimp were soaked in a 2% (wt salt /wt shrimp) sodium tripolyphosphate (Brifisol 512, BK Ladenburg Corp., Cresskill, NJ) solution and stored in a refrigerator overnight before thermal conductivity (Tc) measurements.

Measurement of dielectric properties

A Hewlett-Packard 85070B open-ended coaxial-line probe and 8510B Network Analyzer (Hewlett-Packard Company, Santa Rose, CA) were used to measure dielectric constant and loss factor from 0.2 to 20 GHz at 7 to 90°C with 5°C intervals.

A device with a stainless steel sample cup (i.d. 18.95 mm and ht 19.05 mm), a Delrin water jacket, supporting platform and Haake Instruments Model FK Constant Temperature Circulator (Nelson et al., 1996) was used to control the temperature. Sample was cut into pieces (dia. 18.95 mm and ht < 19.05 mm) after removal of the surface layer of the tissue. To avoid change in density, sample was gently placed into the cup and the probe was placed on the surface of the sample. Then the whole device was fixed firmly to the holder and temperature was increased. Sample temperature was monitored with a Nylon-insulated duplex copper-constantan thermocouple (No. 36-gauge) inserted in a 15-mmdeep, 0.9-mm-dia hole drilled vertically into the 1.64-mm-thick side wall of the sample cup. The thermocouple was connected to a Digi-Sense JTEK Thermocouple Thermometer (Cole-Parmer Instrument Company, Niles, IL). The dielectric probe was calibrated with distilled water before sample measurement.

The dielectric constant (ϵ') and loss factor (ϵ'') at frequencies of 915 MHz and 2450 MHz were selected for calculation of penetration depth (d_p) for these samples (Buffler, 1993):

$$d_P = \frac{\lambda}{\sqrt{2}\pi\sqrt{\epsilon'\sqrt{1 + (\epsilon''/\epsilon')^2} - 1]}} \quad (1)$$

where $\lambda = 12.2$ cm at 2450 MHz; $\lambda = 32.8$ cm at 915 MHz.

The polynomial models of changes in dielectric constant, loss factor and microwave penetration depth for both marinated and nonmarinated shrimp and catfish with temperature were calculated using *SigmaPlot Scientific Graphing Software (version 2.01)* (Jandel Scientific, San Rafael, CA).

Thermal conductivity (Tc) measurement

The Tc of samples were measured in a temperature range from 10 to 70°C at intervals of 10°C. The line heat source probe method was used for Tc measurement (Sweat, 1986). The Tc probe used was constructed as described by Sweat (1986). A 21-gauge hypodermic needle of 0.80-mm dia and 38-mm l was used. A constantan wire, 0.076 mm in dia, was used as heat line source. The measurement was run for 120 sec with a constant current supply of 400 mA. Temperature was recorded 4 times per sec by a PC computer. The Tc (k) of the sample was calculated with the equation provided by Sweat and Haugh (1974):

$$k = Q/4\pi s \quad (2)$$

where Q is the heat supplied by the probe (in W/m) and s is the slope of the line for temperature vs *ln* (time). Each data point was replicated at least 6 times. Since the slope of temperature and *ln* (time) line was affected by the selection of time span, a time span of 10 to 35 sec was used to minimize slope variability. Slope with coefficients of determination (R^2)>0.995 was selected. The probe was calibrated with both 0.5% agar gel and glycerin at 30°C during the measurement. In this study, the slopes for 0.5% agar gel and glycerin at 30°C were 0.81 ± 0.02 and 1.73 ± 0.01. Since the electrical resistance of the constantan wire was constant, the standard Tc of 0.628 W/m°C for 0.5% agar gel (Sweat and Haugh, 1974) was used to calculate the total energy supplied by the probe. Thermal conductivity of glycerin at 30°C was then calculated from Eq (2). The value of 0.293 ± 0.003 W/m°C was near published value of 0.284 W/m°C (Perry and Green, 1984). Thus, the system was satisfactory for quick Tc measurement with dependable accuracy and reproducibility.

For marinated shrimp, the probe was inserted into the center of shrimp and completely covered by shrimp. For marinated catfish, samples were cut into 25 mm by 70 mm strips. Three strips were stacked together as one sample and wrapped with plastic film. The probe was inserted in the center strip and completely covered by sample. The ratio of probe dia to both shrimp and catfish sample dia was in the range 0.43–0.03 recommended by Sweat et al. (1973). Samples were precooked in the microwave oven to quickly raise the temperature. Then the sample was rapidly placed into a whirl-pack plastic bag (Fisher, Pittsburgh, PA), the probe was inserted, totally covered with sample and placed in the water bath to further raise the temperature. Once the temperature difference between sample and water bath was <1°C, the measurement was started. The moisture content and water-holding capacity of samples were measured after Tc measurement.

Moisture ash and water holding capacity

The moisture and ash contents of samples were determined by AOAC (1995) procedures of 934.01 and 938.08. The water-holding capacity of shrimp and catfish samples was determined by the modified method of Jiang et al. (1985). After measurement of Tc, samples were cut into 2 portions. One portion was used for determination of moisture content. The other was chopped and wrapped with a nylon net and 3 pieces of filter paper (Whatman No. 44). The wrapped samples were centrifuged at 3000 × *g* for 20 min. The percentage ratio of sample weight difference between before and after centrifuge, to the sample weight before centrifuge provided free water content. The difference between moisture content and free water content was described as the water-holding capacity index.

Data analysis

The Statistical Analysis System (SAS, 1987) was used to analyze data with the general linear model (GLM) and Pearson correlation procedure. The level of significance for all tests was $\alpha = 0.05$. Mean separations were evaluated according to Duncan's Multiple Range Test.

RESULTS & DISCUSSION

Dielectric properties of marinated shrimp and catfish

For microwave heating, the commonly used frequency is 2450 MHz, although 915 MHz is used in some industrial microwave ovens. Therefore, dielectric properties at both frequencies, 2450 MHz and 915 MHz, were determined. The dielectric constant and loss factor depend on frequency and temperature as well as on bound and free water content and ionic conductivity (Calay et al., 1995).

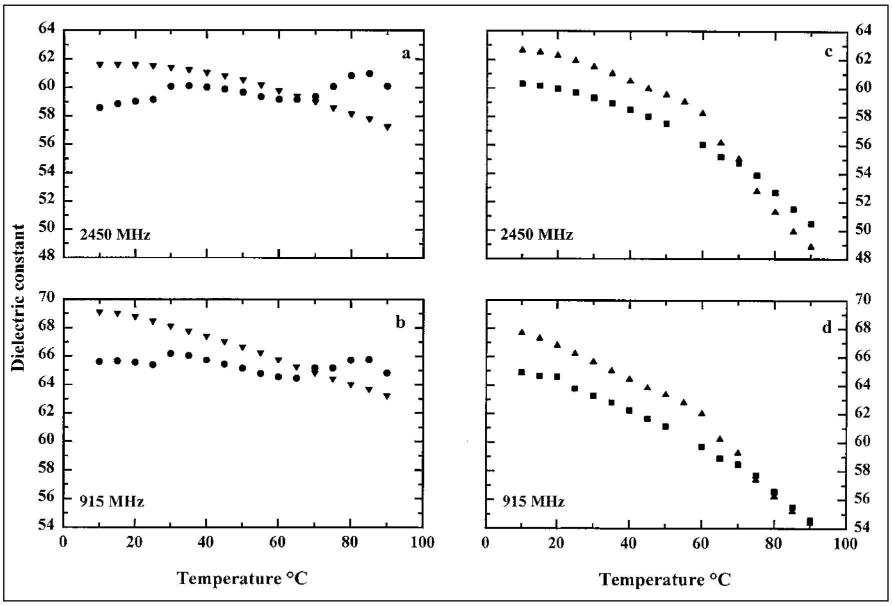

Fig. 1—Changes of dielectric constant of marinated shrimp and catfish with temperature at microwave frequencies of 2450 MHz and 915 MHz. Fig. 1a and 1b: (●) nonmarinated shrimp; (▼) marinated shrimp; Fig. 1c and 1d: (■) nonmarinated catfish; (▲) marinated catfish.

As the microwave frequency decreased from 2450 MHz to 915 MHz at constant temperature, the dielectric constant and loss factor of both marinated and nonmarinated samples increased (Fig. 1 and 2). At a fixed frequency, dielectric constants of all samples decreased with increasing temperature, except for a slight increase of dielectric constant of nonmarinated shrimp with increasing temperature (Fig. 1). Loss factors of all samples increased with increasing temperature (Fig. 2). The observations were in agreement with data on temperature dependence of the dielectric constant and loss factor for beef, turkey, fish, pork, and potato (Ohlsson et al., 1974; To et al., 1974; Ohlsson and Bengtsson, 1975). In comparison to the dielectric properties of nonmarinated samples, marinated shrimp and catfish exhibited a tendency for greater dielectric constants when cooking temperature was <60°C. Marinated shrimp and catfish had higher loss factors than nonmarinated samples. Salting a product reduced the free water content and depressed the dielectric constant and dipolar loss, but the ion conductive losses increased (Calay et al., 1995). The increases of loss factor in marinated shrimp and catfish could be explained as the increase of conductivity loss in marinated samples due to the increase of ion concentration (ash content increased).

Penetration depths for samples were calculated from the dielectric constant and loss factor. Penetration depths of the microwave for all samples (Fig. 3) decreased with increasing temperature. The lower the microwave frequency, the deeper the energy can penetrate into the samples. Microwave penetration depth for marinated shrimp and catfish decreased because of higher loss factors. As a result, more microwave energy was dissipated in the surface layers of marinated foods. The changes in dielectric constant, loss factor (Table 1) and microwave penetration depth (Table 2) for both marinated and nonmarinated shrimp and catfish with temperature were fitted with a polynomial model.

Table 1—Models for dielectric properties as a function of temperature

Sample	Model	
Dielectric Constant at 915 MHz		
Nonmarinated shrimp	$65.00 + 7.49*10^{-2}T - 2.21*10^{-3}T^2 - 2.0*10^5T^3$	$R^2 = 0.612$
Marinated shrimp	$69.86 - 5.25*10^{-2}T - 2.5*10^{-4}T^2$	$R^2 = 0.999$
Nonmarinated catfish	$65.56 - 4.83*10^{-2}T - 8.0*10^{-4}T^2$	$R^2 = 0.999$
Marinated catfish	$67.79 - 1.71*10^{-2}T - 1.5*10^{-3}T^2$	$R^2 = 0.997$
Dielectric Constant 2450 MHz		
Nonmarinated shrimp	$56.98 + 1.81*10^{-1}T - 3.8*10^{-3}T^2 - 3.0*10^5T^3$	$R^2=0.779$
Marinated shrimp	$61.66 + 9.49*10^{-3}T - 6.6*10^{-4}T^2$	$R^2=0.999$
Nonmarinated catfish	$60.33 + 7.28*10^{-3}T - 1.3*10^{-3}T^2$	$R^2=0.999$
Marinated catfish	$61.82 + 7.46*10^{-2}T - 2.5*10^{-3}T^2$	$R^2=0.996$
Loss Factor at 915 MHz		
Nonmarinated shrimp	$26.88 + 7.09*10^{-2}T + 4.4*10^{-3}T^2$	$R^2 = 0.999$
Marinated shrimp	$43.71 + 3.85*10^{-1}T + 3.0*10^{-3}T^2$	$R^2 = 0.999$
Nonmarinated catfish	$20.43 + 1.53*10^{-1}T + 5.4*10^{-4}T^2$	$R^2 = 0.998$
Marinated catfish	$26.06 + 7.80*10^{-1}T - 3.3*10^{-4}T^2$	$R^2 = 0.991$
Loss Factor at 2450 MHz		
Nonmarinated shrimp	$22.60 - 9.48*10^{-2}T + 2.2*10^{-3}T^2$	$R^2 = 0.997$
Marinated shrimp	$29.23 + 3.58*10^{-2}T + 1.6*10^{-3}T^2$	$R^2 = 0.999$
Nonmarinated catfish	$19.22 - 1.32*10^{-1}T + 2.4*10^{-4}T^2 - 1.0*10^{-5}T^3$	$R^2 = 0.992$
Marinated catfish	$24.46 - 1.43*10^{-1}T + 6.1*10^{-3}T^2 - 4.0*10^{-5}T^3$	$R^2 = 0.994$

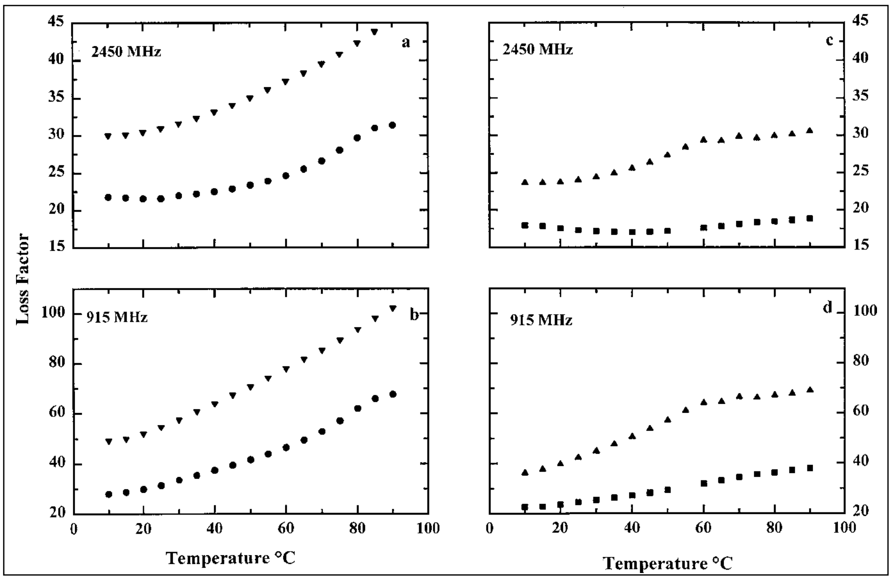

Fig. 2—Changes of loss factor of marinated shrimp and catfish with temperature at microwave frequencies of 2450 MHz and 915 MHz. Fig. 2a and 2b: (●) nonmarinated shrimp; (▼) marinated shrimp; Fig. 2c and 2d: (■) nonmarinated catfish; (▲) marinated catfish.

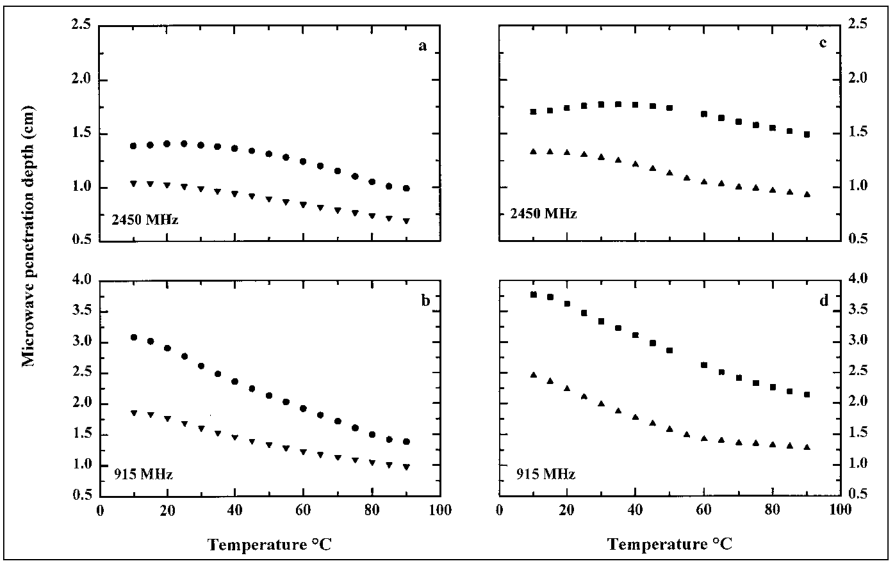

Fig. 3—Changes of microwave penetration depth for marinated shrimp and catfish with temperature at microwave frequencies of 2450 MHz and 915 MHz. Fig. 3a and 3b: (●) nonmarinated shrimp; (▼) marinated shrimp; Fig 3c and 3d: (■) nonmarinated catfish; (▲) marinated catfish.

Thermal conductivity of marinated shrimp and catfish

Thermal conductivity of shrimp and catfish showed slightly increasing trends with temperature. No significant correlation between temperature and Tc of shrimp and catfish was found. Although Tc of food materials were changed with moisture content, the changes in moisture content for marinated, nonmarinated, and 2% tripolyphosphate-treated shrimp were <3%, and for catfish were <4.8% at temperatures below 60°C (Table 3). These small changes in moisture did not affect thermal conductivity. At given temperatures, 2% sodium polytriphosphate-treated shrimp had higher Tc than either marinated or nonmarinated shrimp (Table 3) as a result of higher moisture content. Overall, Tc

Table 2—Models for microwave penetration depth as a function of temperature

Sample	Model	
915 MHz		
Nonmarinated shrimp	$3.426 - 2.92*10^{-2}T + 7.0*10^{-5}T^2$	$R^2 = 0.999$
Marinated shrimp	$2.073 - 1.76*10^{-2}T + 6.0*10^{-5}T^2$	$R^2 = 0.998$
Nonmarinated catfish	$4.133 - 2.90*10^{-2}T + 7.0*10^{-5}T^2$	$R^2 = 0.998$
Marinated catfish	$2.818 - 3.41*10^{-2}T + 1.9*10^{-4}T^2$	$R^2 = 0.998$
2450 MHz		
Nonmarinated shrimp	$1.389 + 2.37*10^{-3}T - 8.0*10^{-5}T^2$	$R^2 = 0.996$
Marinated shrimp	$1.093 - 3.11*10^{-3}T - 2.0*10^{-5}T^2$	$R^2 = 0.998$
Nonmarinated catfish	$1.663 + 5.84*10^{-3}T - 9.0*10^{-5}T^2$	$R^2 = 0.987$
Marinated catfish	$1.430 - 6.06*10^{-3}T + 3.6*10^{-6}T^2$	$R^2 = 0.989$

Table 3—Thermal conductivity (W/m°C) of marinated shrimp and catfish as a function of temperature[a]

Sample	No. replicates	Temperature						
		10 °C	20 °C	30 °C	40 °C	50 °C	60 °C	70°C
Nonmarinated shrimp								
Mean	16	0.41bC	0.44bB	0.48bA	0.48cA	0.48bA	0.49bA	0.50aA
Std. Dev.		(0.08)	(0.04)	(0.06)	(0.03)	(0.02)	(0.04)	(0.04)
Marinated shrimp								
Mean	16	0.38bC	0.46bB	0.45bB	0.47cB	0.50bA	0.50bA	0.50bA
Std. Dev.		(0.07)	(0.02)	(0.03)	(0.02)	(0.01)	(0.02)	(0.03)
2% Sodium tripolyphosphate-treated shrimp								
Mean	8	0.47aC	0.51aB	0.55aA	0.52bAB	0.52aAB	0.53aAB	0.52abAB
Std. Dev.		(0.01)	(0.03)	(0.06)	(0.01)	(0.01)	(0.00)	(0.02)
Nonmarinated catfish								
Mean	8	N.D.	0.48aB	0.53aA	0.52bA	0.54aA	0.54abA	0.51abA
Std. Dev.			(0.04)	(0.03)	(0.02)	(0.03)	(0.02)	(0.03)
Marinated catfish								
Mean	8	N.D.	0.49aC	0.52aB	0.56aA	0.52aB	0.54aAB	0.53aAB
Std. Dev.			(0.03)	(0.03)	(0.01)	(0.03)	(0.02)	(0.02)

[a]Means within a column in same type of seafood followed by a common lower-case letter and means within a row followed by a common upper-case letter are not significantly difference (= 0.05). N.D. not determined.

Table 4—Moisture content (%) of marinated shrimp and catfish as a function of temperature[a]

Sample	No. replicates	Temperature						
		10 °C	20 °C	30 °C	40 °C	50 °C	60 °C	70°C
Nonmarinated shrimp								
Mean	16	76.2 bA	74.9cB	76.0bA	75.9bA	74.6cB	74.2bBC	73.7bC
Std. Dev.		(1.5)	(1.0)	(0.8)	(1.3)	(1.3)	(1.4)	(0.9)
Marinated shrimp								
Mean	16	75.6bA	75.7bA	75.6bA	75.2bAB	75.6bAB	75.0bB	73.8bC
Std. Dev.		(0.4)	(0.7)	(0.7)	(1.2)	(0.8)	(0.5)	(0.6)
2% Sodium tripolyphosphate-treated shrimp								
Mean	8	80.1aA	80.3aA	79.3aAB	79.7aAB	79.0aB	77.9aC	77.2aC
Std. Dev.		(1.1)	(0.5)	(0.6)	(0.9)	(0.9)	(0.4)	(1.7)
Nonmarinated catfish								
Mean	8	N.D.	78.6aA	78.1aA	76.0aB	75.8aB	74.8aB	69.7aC
Std. Dev.			(0.9)	(0.9)	(0.7)	(1.8)	(1.3)	(2.8)
Marinated catfish								
Mean	8	N.D.	78.0aA	78.5aA	77.3aA	77.1aA	76.5aA	70.8aB
Std. Dev.			(2.3)	(1.5)	(1.6)	(1.1)	(1.7)	(1.2)

[a]Means within a column in same type seafood followed by a common lower-case letter and means within a row followed by a commom upper-case letter are not significantly difference at the 0.05 probability level. N.D. means not determined.

for marinated and nonmarinated shrimp and catfish were constant. Thus, the Tc of all five samples was considered constant over the range 10 to 70°C. The mean Tc were 0.47±0.05, 0.47±0.06, 0.52±0.04, 0.52±0.03 and 0.52±0.03 W/m°C for marinated shrimp, nonmarinated shrimp, 2% sodium tripolyphosphate-treated shrimp, marinated catfish, and nonmarinated catfish, respectively.

Moisture and ash contents of shrimp and catfish

The moisture contents of raw shrimp before and after marination were 76.2%, 75.6%, while that of the catfish were 78.6% and 78.0%. Ash contents for raw shrimp before and after marination were 1.64%, 2.44%, while those for catfish were 1.03% and 2.16%. No significant differences in moisture contents of either shrimp or catfish were found regardless of marination. However, the ash contents of marinated shrimp and catfish were significantly higher than that of nonmarinated samples as the salt and spices were incorporated into the sample during marination.

In the study of Tc, the moisture content of all 5 samples was slightly decreased when samples were heated above 60°C as shown (Table 4). The shrimp treated with 2% sodium tripolyphosphate had higher moisture content than both marinated and nonmarinated shrimp. Sodium triphosphate has been used in the food industry to increase the water content of meat products. No differences in moisture content between marinated and nonmarinated shrimp or catfish were found regardless of cooking temperature except that for shrimp at 20°C.

Water-holding capacity of shrimp and catfish

Water-holding capacity of shrimp decreased at 50°C when cooking temperature reached 50°C regardless of treatment (Table 5). This result was due to the muscle denaturation of protein. Water-holding capacity of marinated shrimp was lower than nonmarinated shrimp from 40 to 70°C. With marinated catfish a similar reduction in water holding capacity was evident at 60°C. However, no significant water-holding capacity differences were found for nonmarinated catfish at 40, 50 or 70°C.

CONCLUSIONS

MARINATION INCREASED THE DIELECTRIC loss factor and decreased penetration depth of the microwave on shrimp and catfish due to addition of salt and spices. The temperature difference from surface to the center of marinated seafood was greater than for nonmarinated samples. Marination altered temperature distribution and therefore might influence inactivation characteristics of microorganisms during microwave cooking. The effect of different types of marination solutions on dielectric properties should be measured precisely to enable estimating their impact on microbiological safety of the microwave cooked products.

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Table 5—Water-holding capacity (%) of marinated shrimp and catfish as a function of temperature[a]

Sample	No. replicates	Temperature 10 °C	20 °C	30 °C	40 °C	50 °C	60 °C	70°C
Nonmarinatd shrimp								
Mean	16	54.8aB	54.9aB	52.6aC	57.9aA	44.5aD	39.3aE	41.2aE
Std. Dev.		(2.9)	(2.9)	(2.9)	(5.0)	(2.7)	(2.0)	(1.9)
Marinated shrimp								
Mean	16	52.6aA	53.48aA	51.0aA	53.2bA	37.8bB	36.3bB	36.0bB
Std. Dev.		(3.4)	(4.67)	(4.9)	(4.2)	(3.7)	(19.0)	(1.7)
2% Sodium tripolyphosphate-treated shrimp								
Mean	8	47.0bBC	48.9bB	45.2bC	52.1bA	38.0bD	34.1bE	35.6bDE
Std. Dev.		(2.4)	(2.4)	(4.9)	(1.7)	(2.0)	(2.7)	(2.2)
Nonmarinated catfish								
Mean	8	N.D.	43.3bA	42.7bA	39.3aA	42.2aA	43.6aA	38.9aA
Std. Dev.		N.D.	(2.0)	(1.6)	(2.8)	(5.2)	(4.2)	(3.9)
Marinated catfish								
Mean	8	N.D.	58.3aA	57.8aA	39.9aB	36.3aB	37.4bB	40.7aB
Std. Dev.		N.D.	(3.5)	(4.2)	(3.4)	(5.2)	(5.1)	(3.7)

[a]Means within a column in same type seafood followed by a common lower-case letter and means within a row followed by a common upper-case letter are not significantly difference at the 0.05 probability level. N.D. means not determined.

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Ms received 7/1/97; revised 1/27/98; accepted 2/6/98.

The study was supported in part by the University of Georgia Agricultural Experiment Station, Sea Grant College Program, and National Fisheries Institute. We thank Drs. Y.C. Hung and P. Mallikarjunan for valuable assistance.